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THE SPACEBORNE GLOBAL CLIMATE OBSERVING SYSTEM (SGCOS)

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PREFACE

Our national planning for the Spaceborne portion of the Global Climate Observing System is behind schedule. This report is prepared in parallel with several others to accelerate our progress in this key area of space applications. Within the setting of the emerging possibilities of space platforms and shuttle-borne pallets, as well as the changing opportunities for research satellites and research experiments on operational satellites, and within the emerging European Space Agency plans and the accomplishments of other nations, this report seeks to strike a balance between the accomplishments of the present and the practicalities of the future.

The discussions and study reported in this document began in Fall, 1980 with David Atlas of NASA and continued for more than 12 months with many other scientists and engineers. During this time, NASA's Weather and Climate program sponsored several major reviews and symposia which related to the problem of the Spaceborne Global Climate Observing System (SGCOS). The first of these was the Climate Observing System Study (NASA, 1980) prepared by the Laboratory for Atmospheric Sciences at Goddard Space Flight Center in September, 1980. The second major study, organized by the same group, was the Workshop on Precipitation Measurements from Space (NASA, 1981). We carried out our independent, yet interrelated, study at the Research Institute of Colorado within the setting of these and other national and international meetings. Thus, the present document will certainly not attempt to summarize or repeat the results already presented from the recent workshops and meetings, but will focus on (a) adding new ideas to the conceptual planning of the Spaceborne portion of the Global

Climate Observing System (SGCOS), and (b) discussing in a retrospective manner the results from the large gatherings insofar as the opinions of the authors' are concerned.

In order to keep the study viewpoint broadened, we enjoyed the collaboration of Professor Ehrhard Raschke of the Federal Republic of Germany. He has an extensive background of research with both the United States' scientific space program and the European Space Agency. We also drew upon ideas and suggestions from many of our other colleagues and thank them all for their contributions.

Thomas H. Vonder Haar

Principal Investigator

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Appendix D: The Climate Observing System (COS)-TEST
Appendix E: Bibliography of Related Publications
Appendix F: List of Acronyms
Appendix G: Other Scientific Papers Supported by the Present Contract:

- Vonder Haar, T. H., 1981: Climate Observations from Space in the 1980's. [IN] Space-enhancing Technological Leadership, Vol. 44, Advances in the Astronautical Sciences, edited by Lawrence P. Greene for the American Astronautical Society.

- Vonder Haar, T. H. and E. A. Smith, 1981: Combined Spaceborne and Conventional Measurements for Precipitation Estimation. Proceedings of Workshop on Precipitation Measurements from Space, D. Atlas and O. Thiele, editors, GSFC, pp. D-176-D-183.

- Vonder Haar, T. H., 1980: Exploiting Existing Operational and Research Satellites for Climate Purposes. Proceedings of the First Climate Observing System Study Workshop, NASA, Greenbelt, MD. 21-22 February.

[1] Several appendices listed in the Table of Contents are part of this official report to NASA. Because of their bulk, they are bound and distributed separately from the main body of the report. Contact the senior author or technical monitor for copies of the appendices.

EXECUTIVE SUMMARY

The Spaceborne Global Climate Observing System (SGCOS)

by

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June, 1982

This report has been prepared at the request of NASA's Office of Space and Terrestrial Applications and its Goddard Laboratory for Atmospheric Science. It serves as a "strawman" document for consideration by NASA as implementation of the Spaceborne U. S. portion of the Global Climate Observing System (SGCOS) is finalized. The authors, all professors of atmospheric science, drew upon their many years of experience in the design and analysis of data from meteorological satellites, ground and aircraft platforms. They are all active participants in national and international weather and climate research programmes.

The report is based on the recognized requirements for measurements leading to an improved understanding of the physical basis of climate, climate applications and economic assessment and climate information systems (NASA, 1977). In addition, the authors preface their study with a few fundamental factors to be considered in the design of the emerging climate observing system.

The importance of measuring physical <u>indices</u> of climate, as well as the basic climate parameters, is such a factor. These indices can contribute greatly to both climate modeling and climate diagnostic studies. In general, we emphasize throughout the document that climate study involves

the regular, stable measurement of indices, changes, trends, rates, and gradients. The 1977 NASA document did not emphasize these aspects of climate measurement.

The two types of climate studies, modeling and monitoring, are held to be of equal priority in considering the design of the climate observing system. Climate modeling objectives are not primary. The SGCOS must also serve wherever possible to augment and interface with already longterm monitoring of the fundamental climate parameters of surface temperature, precipitation and solar energy supply. Adequate monitoring (of changes, trends, etc.) alone, without modeling or diagnostic analysis, can support valuable statistical-actuarial climate studies.

Certain key climate regions for observation and experimentation are stressed. This factor influences the design of the spaceborne GCOS in that emphasis is shifted to key regions, times and parameters above and beyond background global measurements.

International and national factors are also fundamental to the design of the SGCOS in the U.S. The World Climate Research Program is a reality. The U.S. Congress and executive agencies are preparing the U.S. Climate Program. Scientists in the U.S. are committed to a longterm, quantitative study of climate with a focus on the interannual variability of the annual cycle.

Climate research and applications assessment must be joined with common data reduction, management and dissemination to the community. The spaceborne GCOS must be an identifiable system to be managed, yet integrated in part into the operational weather system.

The approach of this study was:

(a) define the SGCOS of the 1990's;

(b) consider small additions or modifications to the present (1980) system of operational and experimental satellites that would enhance their use for climate purposes;

(c) consider the incremental steps necessary to move from the present satellites to SGCOS in 1990, including the necessary technological developments.

The Spaceborne U.S. portion of the Global Climate Observing System for the 1990's should be dominated by a new generation of geostationary satellites. These SUPER-GEOS will provide high resolution passive microwave measurements of precipitation and other variables as well as multi-spectral imaging with very high time and space resolution. Two or three low earth-orbiting satellites (LEOS) will complete the SGCOS and serve as platforms for active sensors, solar output and ice monitors and other sensors similar to those on the SUPER-GEOS. Such "twin" sensors flown on both LEOS and GEOS allow important intercalibration, thus binding the SGCOS into a true system. Both Space Platform and Space Pallet concepts are considered as important components of the overall effort.

Other SGCOS configurations considered, but not recommended at this time, included (a) larger numbers of LEOS teamed with 1980-type GOES, (b) a fleet of very large maneuverable LEOS carrying complex sensors operated in a man-interactive (e.g., SPACE TELESCOPE) mode, and (c) fleets ($\sim$100) of small low-cost satellites launched from Shuttle.

Attainment of SGCOS in 1990 begins with a practical appraisal of the present-day satellite system from the climate data point-of-view. It is found that improved data analysis procedures can yield important climate information from the existing system, especially in terms of cloud, wind and mass field indices. Measurements of certain key climate parameters such as solar output, earth radiation budget, ozone and stratospheric aerosols are being made or are already planned for the 1980's. It is very important that these measurements continue! Thus, a climate record from satellites has already begun to meet some of the national and interational requirements. Small additions and/or modifications to the 1980's system could yield major increases in climate information (e.g., by stabilizing the temperature and moisture sounder instruments, by using ground-truth to derive and test precipitation indices from satellite microwave data, and by restoring a basic sea ice monitoring instrument). Finally, certain new technology is absolutely required, notably the new SUPER-GEOS satellites.

We emphasize that it is essential to perform sampling studies of the temporal and spatial variance of all key climate parameters and indices as soon as possible. Based on the studies and on other factors, sampling strategies to optimize observing systems can then be determined.

The report concludes with a further reminder that scientific data processing and dissemination must be given high priority. The Space Science Board's CODMAC (1981) Scientific Data Management Unit concept is endorsed as the best mechanism.

1.0 Background and Purpose

Origins of the present-day World Climate Programme can be traced to the Wijk conference (JSC, 1974) where the plan to study the physical basis of climate and climate change was laid in an international setting. Important impetus for the plan came from the emerging World Weather Watch and the Global Weather Experiments in 1979. Both WWW and GWE draw heavily upon the new observing technologies, including satellites, and upon large digital computers to process data and examine it using complex models.

COSPAR (1980) at the international level and various national groups began to focus upon plans to use satellites as part of the Global Climate Observing System (GCOS). At a worldwide level, the International Satellite Cloud Climatology Project for 1983-1987 (JSC, 1982) is the first of several satellite-based projects designed to meet objectives of the World Climate Research Programme. The U.S. Earth Radiation Budget Experiment (ERBE), 1984-1986, is a distinct spaceborne climate experiment. Climate-related projects are SAGE on ERBE and SBUV on TIROS-N among others.

Recently, the U.S. Climate Dynamics Panel has identified a research strategy for climate (NAS, 1978) and has accepted the National Climate Program Five-Year Plan (NOAA, 1980). Even earlier a group of scientists met at Goddard Space Flight Center (NASA, 1977) to summarize climate requirements and to outline a possible NASA contribution to the climate program.

In 1980, NASA's Office of Space and Terrestrial Applications asked several groups to prepare "strawman" plans for the spaceborne portion of the GCOS. The activities were to be coordinated by GSFC and the groups involved include the Space Science and Engineering Center, University of

Wisconsin, the Research Institute of Colorado and the National Earth Satellite Service, NOAA.

The present study is the report from the Research Institute of Colorado. Its purpose is to provide guidelines and strategy for a longterm program (e.g., 10 years) for the evolutionary development of a spaceborne climate observing system for research and routine monitoring. It is directed toward NASA and NOAA management as well as the NAS Climate Research Committee, Climate Board, and panels of the Space Science Board!

The following background statements set the stage for our work presented in this report. With the exception of the planetary radiation budget satellite experiments, observations of the important climate variables from space are necessarily indirect. The satellite sensors receive electromagnetic radiation emanating from the earth and its atmosphere. These radiation observations must then be related to the important climate variables. It is this indirect, interpretive step which makes the problem of designing an adequate SGCOS difficult. This sometimes tenuous relationship between what we measure, radiation, and what we really want to observe, temperature, precipitation, etc., suggests that hardware decisions to measure the radiation must be closely linked to the strategy envisioned to produce adequate SGCOS observations or indices of climate. For example, temporal and spacial sampling may be the limiting factors on the accuracy of global precipitation observations or indices regardless of the quality of the radiation measurement from a satellite.

We emphasize that these competing pressures express a need for not only definition of hardware components of SGCOS, 1990 but for definition of

the sampling and interpretation strategies which will yield a result compatible with the requirements of a GCOS. The traditional, and present-day, satellite instrument studies carried out by NASA and the aerospace industry are simply not adequate "per se" for designing SGCOS.

We also emphasize the data management and analysis step after collecting a set of observations from space. NASA is making progress in this area of data reduction with the user in mind but improvement is needed (see CODMAC, 1981). Data analysis, especially of the indirect measurements, is greatly aided by data validation and intercomparison. For this reason, sets of regionally intensive observations using ground- and aircraft-deployed instrumentation are a likely complement to the spaceborne GCOS on a continuing basis.

2.0 Fundamentals of the Spaceborne Global Climate Observing System

Since serious discussion of the Climate Program began in the early 1970's, the basic objectives, observing requirements and potential benefits have been defined and refined. We have chosen as our base requirements those summarized in detail by NASA (1977) - updated as needed.

There are, however, certain additional fundamental factors upon which the design of SGCOS must rest. Those having special influence on our report are discussed in the following sections.

2.1 Monitoring, Modeling and Diagnostic Studies

The climate observing system should be designed to meet three primary needs which are: (a) monitoring of climate over long time periods, (b) modeling of climate to extend our understanding of the physical basis of the climate change, and (c) observations to support diagnostic and process studies. Each of these needs are important in their own right and the entire set provides the basis for a balanced climate observing system to interface with the overall national climate and international climate program.

The monitoring aspect is crucial to document the current climate, to determine the character of climatic variations and to provide early warning of larger variations. Spaceborne observations should also be used to supplement and extend wherever possible surface observations of fundamental climate parameters such as temperature and precipitation.

Climate models are presently viewed as the tools most likely to lead to a better understanding of climate sensitivity and predictability. However, the models must be validated by comparison with observations as a prerequisite. Models should also be used in the design of an observing

system to identify key parameters and the appropriate time and space scales for observations.

Observations to support diagnostic studies are important to increase the understanding of the processes of the climate system. Diagnostic studies also provide insight which leads to better climate models and are useful in identifying problems for model treatment.

2.2 Climate Parameters and Indices

An effective climate monitoring program should use the available observations to the fullest extent possible. The first priority is to monitor physical climate parameters which can be observed directly or inferred from observations. Section 5 discusses the most important parameters and possibilities to observe them. However, such studies clearly indicate some of the important parameters such as soil moisture and precipitation are not readily observable today from space. Fortunately, the fact that some parameters cannot be accurately observed does not mean that information about them is unavailable. It is a normal sequence that a partial understanding is usually sufficient to identify an observable or inferred quantity that is related to the desired parameter. Consequently, a climate index is defined here as a quantity which is related to a climate parameter, perhaps not as uniquely as we would wish, but which carries information about the parameter.

Climatic indices should be an important part of the use of observations. They can contribute to our understanding of processes and to our ability to monitor special aspects of climate. They may continue to be observed in time or may be replaced by climate parameters as our observation capability expands. A few, but by no means complete set of, indices

are included in Table 2.1. They are related to soil moisture, precipitation, surface albedo, net solar radiation at the surface, snow cover, vertical stability, atmospheric water vapor, atmospheric flow patterns, vegetation, frost line, etc. They can, and should be, monitored today. Two examples of new climate indices noted in the Table and observable from satellites are:

(a) A specific climate index called VIRES has been suggested for implementation. VIRES is an acronym for Vertical Infrared Emitting Structure. The VIRES index is simply the broadband infrared weighting function for the upward exitance at the top of the atmosphere. This weighting function can be derived from spectral radiance measurements between 10 and 15 μm. The index is primarily responsive to cloud structure and can distinguish reliably between different cloud and moisture distributions. Appendix C contains a more complete description of the VIRES index by Abel and Cox (1981).

(b) A second index with potential for climatological applications is the horizontal gradient, and perhaps the horizontal flux, of the moist static energy at different levels in the atmosphere. The moist static energy is defined in Equation 1:

$$h = C_p T(z) + gZ + Lq(z) \qquad (1)$$

The three terms on the rhs of (1) have a somewhat curious relationship when inferred separately from satellite data. An understimate of T(z) is often accompanied (or caused) by an overestimate of q(z). Likewise, for middle tropospheric layers an overestimate of T(z) is likely accompanied by an underestimate of T at lower levels thereby decreasing the height z in

TABLE 2.1

Some Climate Indices

Desired Parameter	Index
Soil Moisure	Diurnal range of surface skin temperature
Precipitation	Pressure or absence of cold, bright clouds
Surface Albedo	"Minimum" albedo measured from satellites
Solar Energy Output	Relative solar irradiance at a satellite
Net Solar Radiation at the Surface	Relative planetary albedo weighted by integrated water vapor estimate
Snow Cover, Frost-line, Vegetation	Threshhold of albedo or infrared gradient (time-averaged)
Vertical Stability	MSI (see text)
Water Vapor	Surface temperature weighted by higher level water vapor radiance measurement
Atmospheric Flow Patterns	Net radiation budget gradient
Atmospheric Structure	VIRES (see text and Appendix C)
Eddy Activity in the Atmosphere	Cloud Census

the second term and compensating for the initial overestimate. These compensating relationships may make the moist static energy index (MSI) a very useful tool in monitoring the climate and interfacing climate observations with climate models.

An expanded set of climate indices should be developed and recognized as distinct from climate parameters. Table 2.1 is a beginning.

2.3 Global and Regional Studies

It is convenient to categorize climate monitoring and observing requirements into two categories: global and regional. Global requirements are characterized by a need for a uniform set of observations worldwide; spatial resolution of this global set would allow discrimination of features at least 10^{o} latitude by 10^{o} longitude in horizontal extent. Regional requirements are geographically specific and may include observations not normally acquired in the global category. Such regional observations may serve one or more special purposes: for example, as ground truth for a SGCOS remote sensing technique and sampling philosophy; to detect specific climatic events or trends of significant regional, social or economic importance; to monitor especially sensitive indicators (parameters or indices) of regional or global climate variations; and to serve as boundary conditions and verification data for regional climate models. It must be recognized that the detailed monitoring for the regional studies will not be possible worldwide; the actual number of these regions measured over the long-term will depend upon the degree of success of selected early efforts.

It is important that the "first guess" regional studies' locations and observational requirements be identified early so the design of SGCOS may

proceed. Table 2.2 lists several candidate regional studies and their primary goals.

Table 2.2

Location	Purpose	Crucial Obs. System
N. Atlantic Ocean	a. Support CAGE b. Prec. sampl. study	a. S-GEOS b. LAMMR
Central & North Central N.A. Western Europe	Agricultural support & index development	GEOS
N.E. U.S. & Western Europe	Urban energy requirements & industrial pollutant monitoring	GEOS
N. Africa	Saharan Desert albedo, extent, moisture & energy budget	LEOS
Antarctic Continent	Detect precursers of global climate variations	LEOS
China - High Plateau	Agricultural impacts	LEOS
Arctic Ice Fields	Energy budget of Arctic	LEOS
Indian Ocean, Subcontinent & Himalyan Plateau	Indian summer monsoon	a. S-GEOS b. LAMMR
E. Central Pacific	Ocean-atmosphere studies	S-GEOS

2.4 Required Sampling Studies

The climate indices listed in Table 2.1 and the parameters discussed in Section 5 vary differently in space and time. For instance, the stratospheric temperature and mass field may change during most portions of the year with a time scale of only several days and a space scale over several hundred kilometers. On the other hand, clouds and associated variations of the radiation field change their characteristics over several hundred meters and within minutes.

For the domain of climate monitoring mentioned above it is therefore essential to perform sampling studies of the temporal and spatial variance of all climate parameters. Based upon the sampling studies and feasible instrument concepts optimum observing systems and data handling procedures should be designed.

Several steps are involved:

(a) Study of spatial and temporal variance of the climate parameters on the basis of presently available data sets;

(b) Empirical simulation of the sampling of such parameters with given new satellite systems, ground support and different mesurement techniques (e.g., cross-tracking scanning vs. conical scanning, etc.), based on actual measured data;

(c) Massive numerical simulations in computers.

An optimal observing system may not provide the desired accuracy over all portions of the earth; therefore, in the new sampling studies, increased weighting should be given to "key" climate regions which are discussed in 2.3.

During the past years careful sampling studies have been performed in the U.S. and Europe for satellite measurements of the planetary radiation budget components. These are based on simulated measurements with hemispherical receivers over a varying radiation field. Studies for measurements with higher spatial resolution (to be obtained only with scanning radiometers) were also begun but need more elaborate treatment.

No such studies are known to be available for the other climate parameters that vary with high frequencies in space and time over many portions of the world (e.g., cloudiness, precipitation, surface temperature, etc.). In a recent report, (NASA, 1981), papers by Vonder Haar and Smith (1981), and Laughlin (1981) proposed a beginning to the precipitation sampling study. We have furthermore proposed a more general "COS-TEST" in Appendix D which encompasses the sampling studies required for many key climate parameters.

2.5 Institutional Aspects: National and International

The following statements or revised versions thereof should be considered by NASA for discussion with either the Climate Research Board, the National Climate Program Advisory Board, NOAA, the Joint Scientific Committee of the World Climate Research Program, or COSPAR.

(a) Many of the regional and global observations which are required for the climate program can now be obtained from prior space observations which have not yet been analyzed and/or from existing and operational meteorological satellite systems. A large fraction of these precious data are lost for climate use because they are not now being processed and archived or because they are in such a cumbersome form that make them virtually inaccessible to climate scientists and users. The nation

cannot afford to waste these extremely valuable data resources. While incremental costs involved in processing and archiving these data are not small, they are quite modest in comparison to the costs of replicating them from new observing systems in the future. Furthermore, the costs and difficulty of processing large batches of old data (and the dangers of degradation and loss of magnetic tapes, etc.) greatly exceed those of processing the data in real time for both operational meteorological and oceanic missions and climate monitoring and research. "Tape recording" approaches of the 1960's must be replaced with online, real-time processing of the 1980's.

Unfortunately, NOAA, NESS and NCC lack the funds and manpower either to process and archive old or incoming data for climatic purposes. It is, therefore, critical that such resources be provided and used in new imaginative ways. We also note that the DMSP system provides data of great value to the climate program; however, virtually none of these data are either processed, properly archived, or accessible to the climate community.

Various NASA centers have experimented with data analysis and distribution mechanisms (CODMAC, 1981). In the weather and climate area the recent attempt to centralize the processing of the NIMBUS-7 data (yet subcontract key functions) has been a costly and dismal failure which cannot be repeated. More than three years after launch, scientists still await NIMBUS-7 data! In the age of distributed computing, such centralization is wasteful and unwarranted.

(b) Any global climate observing system which can be visualized involves a combination of low earth-orbiting (LEO) and geosynchronous (GEO)

satellites. Moreover, the climate observing system cannot and need not be separate from the operational meteorological and ocean observing system. The existing NOAA, NESS, and DOD, DMSP meteorological satellites already go a long way toward meeting some climate observing requirements. (This is not to mention existing GEOS of ESA, Japan, and India.) Unfortunately, but for understandable reasons, the DMSP and the NOAA systems are operated independently, so neither their orbits, their instruments, or their ground data handling systems can function harmoniously and synergistically in an integrated operational weather/climate research observing system for climate.

While we are not fully aware of all the special missions of the DMSP system, we believe that an integrated system can be designed which would not impact negatively on those missions, and indeed would probably enhance them. We, therefore, urge that steps be taken to bring the NESS and DMSP satellite systems together <u>in a data output sense</u> to form the beginnings of a comprehensive global observing system.

3.0 Approach of the Present Study

3.1 Purpose of Report

We were asked to set down guidelines and strategy for a long-term (e.g., 10 years) R & D program for the evolutionary development of a routine (operational) climate research space observing system. Such a "Guidelines Document" would be used jointly by NASA and NOAA management as a basis for planning (hopefully, it would also be of interest to DOD). The report would be utilized by the NAS Climate Research Board, NACOA and the NCP Advisory Board as a basis for recommendations to the participating agencies, the President, and the Congress. It may also be utilized by the international community (WMO, ICSU, COSPAR) in planning/developing a global SGCOS for the World Climate Research Program.

3.2 Goals

The climate research and observation program goals shape the priorities and configuration of SGCOS. They were drawn from previous documents such as:

(a) NASA (1977) Contributions to National Climate Program

(b) Five-Year Plan for the U.S.--National Climate Program, NOAA, (1980)

(c) Climate Board NAS (1980) (Woods Hole Report)

(d) Elements of the Research Strategy for the U.S. Climate Program Report of the Climate Dynamics Panel, NAS (1978)

(e) Report of the World Climate Conference, WMO (1980)

(f) COSPAR Report, (1980, et seq.)

(g) Report of the first session of the Joint Scientific Committee for the WCRP and the GARP, JSC (1980)

A summary of the key recommendations of ALL the above reports is, briefly:

(a) To monitor climate around the globe (with regional resolution) to assess what is happening "now" and its likely social and economic impacts; to establish short-term trends (month to seasons) and provide early warnings of impacts; to pay special attention to the annual cycle and its variability.

(b) To monitor climate and representative climatic indices on a long-term basis (i.e., decades); to establish baseline statistics of the space-time variability of climatic factors affecting society and thus allow society to develop strategies to live with and adjust to such variability. Such monitoring of climate will also provide the fundamental statistical base to assess the regional distribution of climatic "signals" and climatic "noise" as a means of determining the basic limitation to climate predictability. This statistical base will also provide the following:

(1) Means of asociating a variety of climate response variables to climate forcing parameters through statistical methods (i.e., searching for teleconnections);

(2) Means of diagnosing those physical factors which have the strongest apparent influence on climate and thus better identify the boundary forcing and climate response variables which need to be observed and modeled to develop prediction methods;

(3) Means of evaluating the performance of climate prediction models and improving them.

(c) To study the key component physical processes which are thought to influence climate (e.g., aerosols and trace gases, radiation and extended cloudiness, air-sea interaction, precipitation, land hydrology and

the cryosphere) and incorporate these processes into numerical predictive models.

(d) To develop and test a hierarchy of outlook or predictive models capable of providing skillful estimates of upcoming climate, first on monthly to seasonal time scales and subsequently on an interannual time scale. This includes the development of models of the atmosphere, the oceans, the cryosphere and the land hydrological cycle, and ultimately coupling them interactively. Observations from space and supporting _in situ_ networks will be required to provide the boundary conditions required to initialize such models and the response variables needed to verify their performance.

(e) To study both the natural and anthropogenic factors (e.g., fossil fuels and CO_2, ozone, agricultural practices and the nitrogen cycle) which influence climate on decadal and longer time scales; to provide early warnings of likely long-term trends which may require major readjustments by society on the national and international scale. For such long-term climatic changes, a special set of observations is required as discussed in other sections.

These goals of our National and World Climate Programs become the goals of the SGCOS.

4.0 SGCOS, The System for the 1990's

Planning for general satellites and experiments of the future (Atlas et al., 1978; Hanson, 1981; Hansen, 1981) is underway as usual. Some specific plans for operational weather satellite systems of the late 1980's and 1990's are among them (Miller and Silverman, 1982). This report focuses upon plans for the climate observing system.

SGCOS, the system of the 1990's represents no radical departure from the progression of satellites and instruments to be used in the 1980's. It does, however, demand a new a special emphasis on stability, continuity and sampling directed toward meeting climate objectives. By the mid-1980's firm decisions on SGCOS based on pilot studies and tests of the kind discussed in this report will reflect better understanding of the relative practicalities of:

(a) new instruments and remote sensing methods,

(b) sampling constraints,

(c) analysis and data processing requirements.

It is highly probable that an optimum SGCOS of the 1990's will be limited by the minimum level of progress in any one of these three key areas.

The recent successful launch of the Space Shuttle has major implications for the near and long-term planning of the Climate Observing System. The Earth Radiation Budget Satellite (ERBS) shown in Figure 4.1 will be the first special climate-related satellite to be placed into orbit by the Space Transportation System (STS). (It is likely to be the first NASA scientific satellite to be launched from Shuttle!) It will use its own rocket engine to atttain 600 km circular orbit with inclination of 52 degrees after insertion at Shuttle altitude. This means that during the

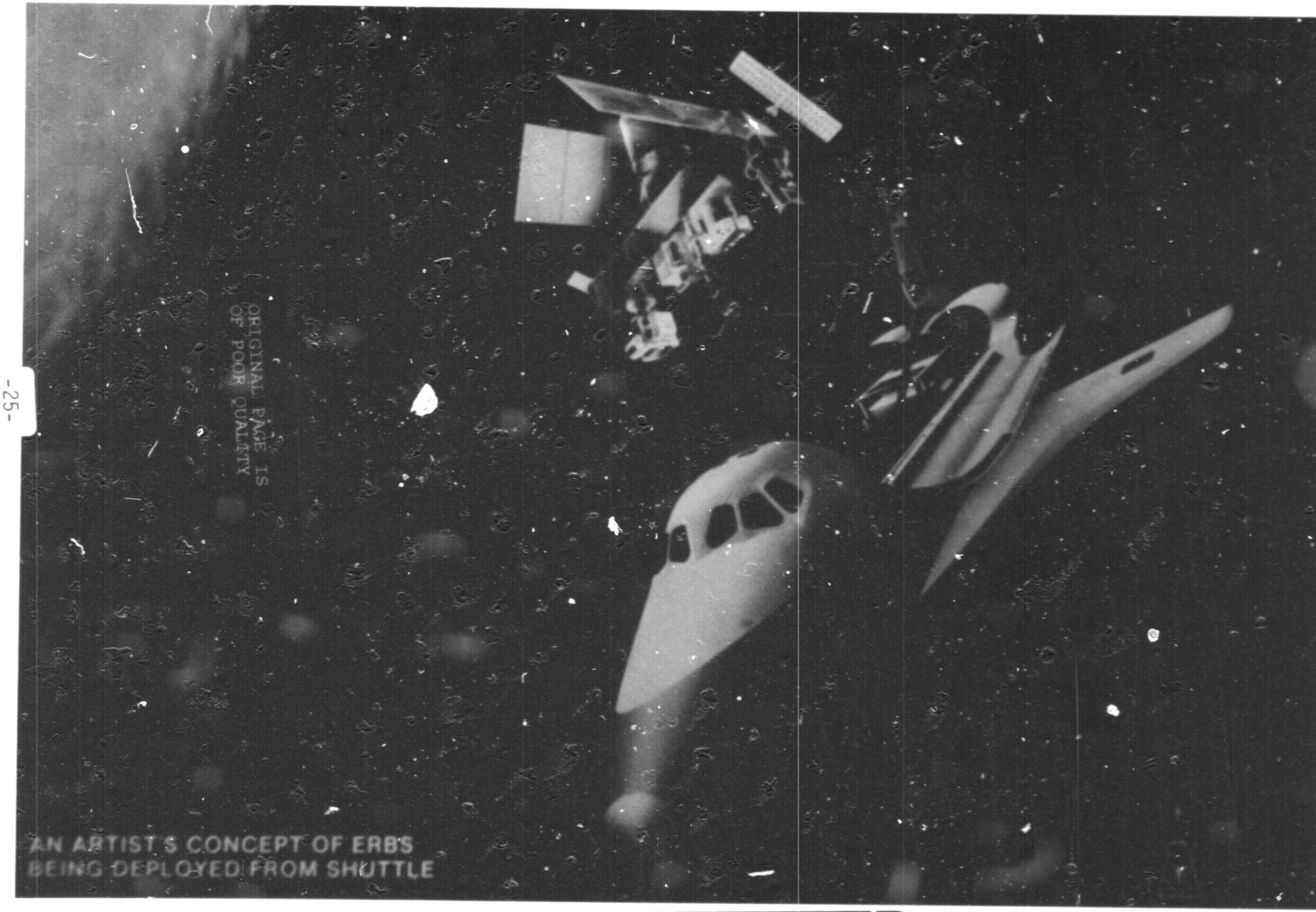

Fig. 4.1 The Earth Radiation Budget Satellite (ERBS).

1984 period and beyond such "small" (4.5 m) relatively "inexpensive" (~ $21M) satellites should be very seriously considered for major components (LEOS, GEOS, or "calibration" satellites) of SGCOS. A single flight of STS devoted to climate would serve to deploy and intercompare in space the primary parts of SGCOS. Intercomparison, so important for the observation of climate rates, indices, trends, etc. from a system of satellites would also be possible using additional Shuttle flights. The new STS capability is thus in accord with principal requirements of SGCOS, namely the use of intercalibrated systems of satellites for stable, long-term climate measurements.

Our study team considered a rather wide variety of candidate satellite systems for SGCOS. The studies were, of course, only conceptual pending the type of computer simulation of sampling and instrument design required for final selection. However, we did discuss:

a) systems of tens (or one hundred) of small, "expendable" LEOS launched economically from the Shuttle,

b) new, very sophisticated, LEOS with orbit adjust capability; such LEOS would be operated in the man-computer interactive mode similar to the SPACE TELESCOPE,

c) larger numbers of presentday LEOS (e.g., NOAA class) teamed with presentday GEOS (e.g., GOES),

d) new SUPER-GEOS satellites teamed with a limited number of small LEOS; such LEOS might be smaller than the NOAA and DMSP satellites, perhaps the size of NASA's new ERBS.

We selected the option (d) above for SGCOS primarily because of the major breakthrough for climate (and weather) to be made with passive

microwave measurement capability from geostationary orbit. In addition, option (d) can use the Shuttle-designed ERBS placed in special orbits to meet climate sampling requirements.

The new developments in technology required for SUPER-GEOS (as well as complementary space platforms and space pallets) are discussed in Section 5.3.

5.0 Attainment of SGCOS in the Next 10 Years

5.1 Climate Additions to the Present Operational and Experimental Satellite Program in the United States

In Table 5.1 we have evaluated our present day capability to observe the most important physical climate parameters from space. The observations are categorized according to "location" in the earth-atmosphere system: top-of-atmosphere, stratosphere, troposphere, ocean surface, and land surface. We have concerned ourselves only with the technology required for these observations and not the sampling inadequacies which will be remedied only by providing more spaceborne platforms in certain orbits.

A check in the A Column in Table 5.1 indicates that the basic technology for this observation is available although it may require some refinement before meeting climate observing requirements. In this section we shall also briefly discuss the annotations in Column B which are viewed as short-term efforts which will transform existing systems into acceptable SGCOS tools in the 1985-1990 time frame.

The annotations in Columns C and D which are larger development efforts in terms of scope and required resources are discussed in 5.2. Note that while the modifications in Column B improve existing satellite compatibility with SGCOS they in general do not meet our expectations of COS in the decade of the 1990's. The actual attainment of SGCOS requires maintenance of accomplishments shown in Column A and the new developments of Columns C and D.

Table 5.1

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Location	Parameter/index	A Possible today	B minor/mod's	C major mod's	D new technology
at top of atmosphere	radiation budget parameters	X	Additional spectral	More platforms!	---
stratosphere	temperature/ mass field	X	Limb sounding	---	---
	H_2O & O_3	X	Limb sounding	---	---
	Other optically active gases	---	Additional spectral channels	Spectral adjustment	---
	Winds	---	From mass field Doppler shift	---	Doppler Lidar tracer's
	Cloud/aerosol	---	Limb sounding	---	Lidar
troposphere	tropopause height/temp.	---	Limb sounders	HIS, AMSU AMTS	Lidar
	wind		Clouds, water vapor displacement	---	Doppler Lidar
	temperature/ thickness	X	---	HIS, AMSU AMTS	---
	H_2 vapor	X	Imagery, sounders	---	---
	cloud properties: top height	(X)	stereo, T_{blk}	Split windows	Lidar
	geom. thickness albedo	---	(reflectance)	---	Radar
	base	---	---	---	---
	LWC	---	(reflectance)	---	Radar
	IWC	---	(reflectance)	---	---
	aerosol optical thickness	---	X	HIS	Lidar
	layer height	---	X	---	LAMMR
	boundary	---	---	AMTS	Polarization
	layer heights	---	---	AMSU	
Land surfaces	precipitation	---	Imagery	DCP's	Radar LAMMR GOES + Passive wave
	vegetation	X	---	---	---
	snow cover	X	---	---	---
	temperature (sfc)	X (cloud free)	---	AMSU(?)	Lidar
	pressure	---	DCP	Microwave	Lidar
	wind	---	DCP	Microwave	Lidar
	albedo	X	---	---	---
	moisture (soil)	---	Thermal inertia	ASMU	Polarization (vis., radar)
	solar insolation	X	---	---	---
Ocean surfaces	precipitation	(X)		---	LAMMR - GOES wave
	temperature	X	Split w., microwave	---	LIDAR, LAMMR
	pressure	---	DCP	Microwave	Lidar
	wind	---	DCP	Scattering	---
	albedo	X	---	---	---
	solar insolation	X	---	---	---
	ice cover	X	---	Optical, microwave	LAMMR
	ocean currents	---	DCP	Altimeter	---

The Earth Radiation Budget Experiment (ERBE) instrumentation promises improvements over earlier experiments. However, the compatibility of current systems such as ERBE with the radiation budget climate requirements at the "top of the atmosphere" may be greatly improved by the following activities. First, the studies of diurnal and angular properties of spectral and broadband radiance fields are essential to the optimum utilization of both LEOS and GEOS data on earth radiation budgers. These studies include utilizing existing data for these determinations, deploying aircraft field measurement programs and some modest satellite hardware modifications or additions.

Stratospheric optically active gases are readily observable from planetary limb observations. In order to observe stratospheric CO_2 some change in strategy and spectral bandpass would be required. It is important that CO_2 concentration in the stratosphere be monitored. However, because of its continuous distribution at lower levels, it may be adequate to be observed from intermittent aircraft excursions into the stratosphere.

Stratospheric winds are determinable in several ways: via the mass field assuming gradient flow, using pseudo-conservative constituents as tracers, and through doppler shifts of limb radiance data. None of these techniques are sufficient in themselves; therefore, we believe that emphasis should be placed upon a doppler lidar system which could dramatically improve the observation of wind and some other parameters as well at these higher levels.

Adequate tropopause height and temperature measurements are close within our reach. Deployment of HIS or AMTS may fulfill this objective.

Doppler Lidar may also be applied to this problem through relationships between the tropospheric wind shear and upper tropospheric aerosol. Tropospheric water vapor and temperature distributions are key parameters in monitoring the atmospheric general circulation. Two of the most obvious shortcomings of current satellite instrument systems are lack of sufficient vertical resolution and absolute accuracy. Particularly important is the ability to discern temperature inversions in the lower troposphere where these inversions define the top of the planetary boundary layer. We are hopeful that the HIS or AMTS instrument will bridge this gap in our observing capability. For climate, the new sounders can be augmented by additional information (e.g., occasional lidar measurements of mean inversion height).

The cloud height and amount requirement has recently been highly prioritized within the World Climate Research Program. The ISCCP (International Satellite Cloud Climatology Project) has been designed to meet this key need using 1980 technology. Its major goal is the derivation of a five-year quantitative cloud data set (spatial resolution: 250 x 250 km^2, temporal resolution: 8 times a day - averaged over 15-day period; cloud parameters: total cloud coverage, fractional coverage in three ltitude ranges and discrimination between cirrus, lower stratiform and deep convective cloud (JSC, 1982).

Cloud thickness, cloud base and cloud radiative properties are difficult to observe directly from space platforms; however, these are critical parameters in the description of the climate system. Strategies for developing at least regional and statistical representations of these variables must be developed. We advocate a combination of satellite,

aircraft and ground-based observations such as the extended cloudiness and radiation program to address this problem area.

Aerosol layer thickness and radiative properties and boundary layer thickness are elusive parameters to determine from space. Although solar spectral reflectances of such features may yield areal extent and total aerosol loading, they do not provide any information on thickness of such features. Here, the spaceborne lidar would be very useful (Atlas and Korb, 1981). The HIS or AMTS may assist in boundary layer identification when a temperature inversion is present such as in the subtropics.

Over land surfaces the observation of precipitation on a global scale is especially difficult because remote sensing in the microwave region is made more complex by the surface. While correlations of satellite visible and IR radiance brightness patterns over both land and water may yield estimates of precipitation amounts, they are not presently adequate for climate purposes. In the interim, it will be useful to exploit the ISCCP data base and to adapt an algorithm for precipitation estimates from this data set.

For the SGCOS, passive microwave instruments deployed on GEOS offer a partial solution for oceanic low and middle latitude locations. This would be an exceedingly important advance. However, precipitation measurements over land may not be satisfied in this way. It would appear that the main hope for these land observations rests on utilization of radar; either spaceborne or a greatly enhanced surface density of radar systems. An alternative might be utilization of DCP's capable of measuring precipitation in key climate regions; however, the spatial sampling problems of such a system would be horrendous at the global scale.

Because precipitation information is so important for climate study we add more discussion in Appendix A of this report. Vonder Haar and Smith (1981) also present a more detailed concept of a system to estimate precipitation. Their study was a portion of the larger Workshop on Precipitation Measurements from Space (NASA, 1981) which presents several strategies for the key precipitation measurement objective. It is important to note that climate requirements for precipitation are in some ways less stringent than the requirements for other applications (e.g., forecasting floods). Again, we also note that key climate regions deserve first attention and that sampling studies are crucial.

The other parameters and indices listed in Table 5.1 pertain to climate and climate processes at the land and ocean surfaces. Some new ideas for the indices were discussed in Section 2.2 of this report. In addition, the NASA (1977) report thoroughly covers the details of present status and minor modifications to the satellite observing systems of the early 1980's insofar as these land and ocean surface climate data are concerned. Our Table 5.1 does place more emphasis than other studies on use of satellite Data Collection Platforms (DCP's) for both land observations and for moored and drifting buoys reporting to satellites over the oceans. This new DCP capability is certain to be better exploited in the next few years for climate purposes.

[1] Several appendices listed in the Table of Contents are part of this official report to NASA. Because of their bulk, they are bound and distributed separately from the main body of the report. Contact the senior author or technical monitor for copies of the appendices.

5.2 Larger Steps Toward SGCOS

As progressive steps, yet major modifications of the present-day systems, we consider the inclusion of new instruments into SGCOS. Some of the instruments are already in development phases. Some of these major modifications have been listed by parameter in Columns C and D in Table 5.1.

In addition to new instruments we must provide new space-time matrices of measurements. Sampling studies have shown that to meet the requirements for measuring the radiation budget parameters and most likely also for precipitation, between three and twelve observations over each earth area are required each day. A major modification of the present satellite systems would, therefore, also require the inclusion of ERBE and precipitation related instruments onto more than one low earth-orbiting satellite (LEO) and possibly several GEOS. In addition, more adequate alignment of the LEOS orbital patterns would be made after more sampling studies have been completed. For the purposes of cloud observations (the ISCCP) and for some other parameters full global coverage must be maintained.

We assume that the basic observing system during the next 5-8 years will be almost identical with that made available for global weather observations. It will consist of:

a) Five GOES (2 from U.S.; 1 from Europe; 1 from India; 1 from Japan) and

b) At least one LEOS (from U.S.) with additional LEOS from Japan (MRS) and Soviet Union (Meteor).

For climate purposes a major development (e.g., for cloud data as per the ISCCP) is the integration and assimilation of the separate satellite

experiments into a true international <u>system</u> of satellites.

Three major new instruments, the high resolution interferometric sounder (HIS), the advanced meteorological temperature sounder (AMTS) and the advanced microwave sounder unit (AMSU) are currently under study in the U.S. for improvement of measurements of atmospheric temperature and water vapor profiles and the surface temperatures. These instruments will also provide more information on cloudiness and the aerosol optical thickness. For measurements of the surface pressure fields an active microwave radiometer is presently being studied jointly at JPL and in the United Kingdom. The inclusion of scatterometers and altimeters (such as investigated first during the SEASAT mission) into an operational system would provide more information on the wind field over ocean surfaces and on ocean currents and ocean eddies.

The steps toward SGCOS thus depend on <u>organized</u> use of present and currently approved satellites and data systems albeit with some new instrumentation. For example, the organization would use available European "climate" satellites:

a) Meteosat 1 and 2 carrying a 3 channel radiometer:

visible (0.5 - 0.7 μm)
water vapor (6.3 μm)
IR window (11 μm)

A well-developed digital archive is provided.

b) ERS-1, etc.

A geoscience satellite programme will be established with a long-term plan. The first satellite (ERS-1) may carry:

Synthetic aperature radar (C-band) with scatterometer
Altimeter
Ocean color monitor
Perhaps other sensors

"Climate" satellites from other nations are described by COSPAR, 1980 and include:

a) INSAT 1 and 2 of India

b) GMS 1,2, etc. & MRS 1,2 of Japan

c) METEOR from the USSR

d) the USA satellites: GOES, NOAA, ERBS, and LANDSAT

Again, we list these well-known climate satellites to emphasize that the second phase, or step, toward SGCOS is the development and use of some new instruments on these well-defined satellites <u>and</u> the organization of the satellite measurements into a system for SGCOS. It is important to note that many of the new instruments have not yet been committed to a spaceflight program and thus there is some urgency for specific plans to be made and implemented (see COSS Report, 1981).

5.3 <u>Highlights of Required New Technology for SGCOS</u>

The requirements for climate parameter and index measurements cannot be fully met by present-day instruments. Some specific accelerated research and development will be required. In addition to the technological innovation in instrumentation, the attainment of SGCOS will require: (a) use of the new Space Platform as a long-term testbed for instruments and some limited sampling studies, (b) the development of a Super-GEOS satellite (especially with passive microwave capability) and (c) development of a Weather and Climate Space Pallet for Shuttle testing of new instrument and calibration concepts.

5.3.1 Instrumentation

In Column D of Table 5.1 we have listed new instrument technology which may be applied to assist in meeting COS objectives. Most of these items/techniques have not yet received sufficient scrutiny to assess their potential contributions. This leads to a note of caution, especially on some of the more expensive systems. We should point out that by listing a new technology in Column D we are not endorsing it at this time. We are suggesting that feasibility and cost analyses be carried out to determine if these systems will provide the required climate data at an affordable cost. Cost includes adequate deployment for climate sampling. Note the recurrence of lidar-type instruments under many of the climate parameter categories.

5.3.2 Space Platforms

Plans for the space platform are beginning to materialize (Snoddy, 1981). This possibility for deploying research sensors is discussed in the present section. The platform will allow sensors to be retrieved for further calibration, an important aspect in some absolute value measurements such as the solar "constant". It will also allow inflight sensor calibration for climate purposes. The space platform, for example, could be the calibration hub of a system of baseline satellies used for meteorology and climatology. If placed in an appropriate earth orbit (perhaps quasi-geostationary) the space platform would underfly all or many of the other satellites working together to provide measurements to comprise a system. In the mid-1980's such a system of satellites will be used for two purposes: (a) the earth radiation budget experiment and (b) the international satellite cloud climatology project. In both cases, one

of the polar orbiting or near polar orbiting free flying satellites is the calibration satellite. These two systems experiments will be important steps forward but unfortunately sensors on the calibration LEOS (NOAA in both cases) will not be recovered for recalibration in the laboratory and thus for validation of the entire absolute calibration of the system. The space platform could provide these additional calibration opportunities for future systems. Furthermore, the platform does not suffer from the short episodic exposure of instruments in the normal Spacelab mission. Certain experiments particularly related to air quality and the detection of low signal to noise climate phenomena such as volcanic aerosols might benefit especially from the recalibration opportunity. In fact, it could be essential to the success of such experiments.

5.3.3 The Space Pallet

For some years the senior author has believed that the a meteorological and climatological pallet carrying standard power, data recording and microprocessor data acquisition systems should be designed and deployed regularly on Spacelab with a variety of new instruments suggested by the research community in atmospheric science and climatology. Such a space pallet would have to be configured for each flight in a standard laboratory calibraton situation that would allow the scientific investigator to complete pre- and post-flight checkouts under the guidance of NASA technicians. The experiments, often of the brassboard variety, would be flown for a short period of time on the pallet attached to the Spacelab. Advantages of such pallet availability would, of course, focus upon the "proof of concept" experiment. The opportunity would be available to test at relatively low cost the new ideas of experimenters. They will

propose to demonstrate a new and perhaps more improved instrument concept or to detect a new atmospheric or oceanic climate signal that has been determined to be marginally feasible based on computer simulations on the ground. The pallet, reusable of course, would take away much of the cost and time between the suggestion of a new idea and the test of that idea from space. We would benefit from an acceleration of our experimental and operational program and from a better pre-selection process for choosing those experiments to fly on the longer mission satellites. Of course, the expense of returning an instrument package to earth, namely the ability to withstand depressurization, is not to be minimized. Thus, there are certain to be rather strict definitions for the configuration of experiments to be tested on the meteorology/climatology space pallet.

The Weather and Climate space pallet is a logical and efficient step in the progression from (computer simulated) concept, laboratory breadboard, balloon or aircraft testing, pallet test, SGCOS deployment. In some cases, it may obviate the costly aircraft or balloon test phase.

5.3.4 Super GEOS

The next generation geostationary satellite presently under study by NESS and NASA as the GEOS-NEXT should undoubtedly be a major step forward in weather and climate observation. Presently, in the early 1980's, we are flying good satellites with 1960-70 technology and GOES-NEXT may be constrained to the same base. However, it is very important that we take advantage of the tremendous technological developments that have accompanied the commercial communication satellite program. These technological developments, including large antennas and large despun platforms in geostationary orbit, represent relatively low risk situations. The

scientific community can now take advantage of these breakthroughs and design its next major thrust, the SUPER GEOS satellite series to take us through the 1990's. GOES-NEXT should be considered only as an interim bridge toward SUPER-GEOS.

Weather and climate research for the late 1980's and early 1990's is being focused in two major thrusts, both very important to the United States. One is the Climate Program which emphasizes the annual cycle and the focus on regional climate variability that influences the energy and agricultural economies of our country. Another major focus is the National Storm Program with its mesoscale emphasis which carries on to the extremely important and economically critical shortrange weather forecasting and its prediction and warning of severe weather. These two main thrusts are forming today and both the GOES-NEXT satellite program and SUPER GEOS should definitely play major roles as supporting platforms to these research thrusts. As they do this, they will also serve to maintain the steady growth of the operational satellite program.

The greatest step forward in geostationary satellites would come from the ability to make passive microwave measurements from that altitude. This possibility should be given the highest research priority both for imaging and sounding. SUPER GEOS would be the host satellite. Results are beginning to be apparent in the literature of the extreme value of the microwave soundings to penetrate most of the cloud cover situations that represent important weather events whose development must be forecast. The microwave imaging for precipitation purposes and for sea surface temperature under the clouds is another example of the extreme need for this capability. The precipitation sampling problem which is so severe as to

preclude precipitation measurements of any net value from polar orbiting satellites alone, can be greatly improved with the high time frequency data sets from geostationary orbits. Precipitation is an extremely important keystone parameter in both climatology and shortrange forecasting including severe weather. The next major step forward for GEOS data would be a lesser but yet very important one; to have much higher vertical resolution infrared sounder data to match the needs of the emerging mesoscale numerical models. Opportunities and test sensors have been developed to demonstrate that such higher vertical resolution is possible by pushing the infrared measurement technology to the utmost. The demonstration of the VAS data in the existing GOES satellites is just a forerunner of the exciting possibilities that would be found with the higher vertical resolution data from SUPER GEOS.

The GOES-NEXT and SUPER GEOS satellites should be designed jointly by NASA and NOAA with weather and climate requirements in mind. A research package of experiments should be included on the GOES-NEXT satellite as well as on SUPER GEOS. NASA and NOAA should plan that from time-to-time one satellite in this series would be dedicated primarily to research and thus would allow the test of a wider variety of sensors. Experiments passing such tests would ultimately take their place in the operational program after proper shakedown in a research mode.

A very important part of the SUPER GEOS and GOES-NEXT system is the ability to broadcast the data in a retransmitted digital mode to many research and operational users at rates of 1 million bits per second or less. The tremendous economies and efficiencies in data dissemination, pre-selection and processing made possible by the broadcast mode should not

be underestimated. The best of instruments and satellite systems meets with only lukewarm user response if data cannot be efficiently and economically utilized by the users. The GOES-NEXT and SUPER GEOS satellites must take advantage of the pioneering retransmission and dissemination available to present GOES users.

6.0 Climate Data Reduction, Management Dissemination, and Analysis

Scientists in recent years have fully recognized the paramount importance of data reduction and processing in the overall scientific experiment or operational application. Many have learned the lesson only after costly delays due to inattention to data processing severely damaged their experiment. Often inefficiencies in data processing have consumed funds originally intended for scientific analysis!

Will the climate data returned by SGCOS encounter the same problems and inefficiencies? It will not if attention is realistically focused early on the management of the data. The Space Science Board CODMAC (1981) report is a new guide for us in these key areas. The SSB committee report counsels efficient, discipline-oriented Scientific Data Management Units (SDMU's). These groups would include a respected core of scientist/data processors who serve the needs of their peers and themselves as they process, document and archive the valued data returned from SGCOS and correlative activities for climate. The report also notes the need to avoid another hazard of data processing; namely, the creation of monolithic "data centers" to provide all things to all users - at great expense.

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